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Antje Nuthmann, and Elke van der Meer

Humboldt University at Berlin

Running Head: Time's Arrow and Pupil Response

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Abstract

The psychological arrow of time refers to our experience of the relentless forward temporal progression of all natural processes. To investigate whether and how time's arrow is mentally coded in individual everyday events, a relatedness judgment task was used. The items each consisted of a verb (probe) and an adjective or participle (target). The temporal orientation between probe and target was varied either corresponding to the chronological orientation (e.g., shrinking – small) or corresponding to the reverse orientation (e.g., shrinking – large). In addition, the interval between probe and target presentation was varied (SOA: 250 ms vs. 1,000 ms). Reaction times, error rates, and pupillary responses were recorded. For both SOA-conditions, chronological items were processed faster than reverse items. These findings suggest that time's arrow is mentally coded in single everyday events. Furthermore, pupil dilation and results of principal component analyses on mean pupillary responses suggest top-down influences in the processing of temporally related probe target pairs.

Key Words: temporal orientation, events, pupillary response, cognitive load

Time's Arrow and Pupillary Response

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The phrase 'time's arrow' was first introduced by Sir Arthur Eddington (1928) in "Gifford Lectures" to describe the irreversible increase of entropy in isolated systems. "An arrow of time is a physical process or phenomenon that has (or, at least seems to have) a definite direction in time." (Savitt, 1995, p. 1). Penrose (1979) was concerned with seven possible 'arrows', including the process of measurement in quantum mechanics, along with its attendant 'collapse of the wave function', the expansion of the universe, and the direction of psychological time. The latter alludes to our experience of the relentless forward temporal progression of all natural processes. Surprisingly, in the microscopic world of atomic particles laws of nature seem to make no difference between forward and backward direction. That is, time's arrow is not found in the basic equations of physics, but only in boundary and initial conditions which are open to explanation (Vollmer, 1985). Therefore, complex questions regarding the nature of time's arrows must be addressed. Sklar (1995) argues in favour of time symmetry at the micro-level, time asymmetry at the macro-level, and no fully compelling connection between the two.

The present study investigates the macro-level, namely the psychological arrow of time. In everyday experience, most event sequences are organized unidirectionally. For example, we can witness the aging of a friend and his death, but we cannot experience this in the reverse order. Friedman (2002) provided evidence that even 8 month old children are highly sensitive to temporal directionality in gravity-related events. These examples point to the existence of a psychological arrow of time, that is, a sensitivity to temporal directionality in real-life events.

It is characteristic for event sequences and events, about which we have background knowledge, that they typically have causal relations of some sort (cf., van der Meer, 2003).

Trabasso, van den Broek, and Suh (1989) differentiated, for example, motivational, physical, psychological, and enabling relations. Riedl (1992) assumed that evolution structured our cognitive system to reflect all environmental events as causally related. Classical conditioning, for example, is based on animals' and humans' disposition to interpret events as causally related, if there is a temporal relationship between them. Most physicists and philosophers agree that there is a hierarchy of causality conditions. "The basic presupposition of the causality hierarchy is that of temporal orientability." (Earman, 1995, p. 274). That is, causality acts toward the future only. This widely accepted approach explains causality by means of time's arrow. Alternatively, one could explain time's arrow by means of causality as proposed by Reichenbach (1956) and Grünbaum (1975). They proposed that time's arrows trace back to a causal arrow. In doing so, the asymmetrical causal relation would be required as an undefined basic concept. However, it remains completely open how events might be identified as either causes or consequences independently from time's arrows (cf., Vollmer, 1985).

The present paper will consider the property of temporal orientability or directionality as a basic presupposition of causality. According to Friedman (2002), there are at present very limited insights into the psychological processes underlying the sensitivity of humans to temporal directionality in real-life events. A question that is fundamental to ask is: Is the psychological arrow of time mentally coded? Freyds (1987, 1992) theory of dynamic mental representations provides a general theoretical framework. She assumes the temporal dimension to be inextricably embedded in the mental representation of the external world and to be directional. Similarly, Barsalou (1999) argues that our mental representations of events are not arbitrary, but do preserve aspects of the initial perceptual and experiential input. For routine events, there is empirical evidence for this assumption. Routines are descriptions of stereotypical, frequently encountered sequences of events (Galambos & Rips, 1982). Several studies demonstrated the preference of the chronological order of routine events compared either with the reverse order or with a random order in using a variety of different paradigms (cf., Mandler & McDonough, 1995; Nelson & Gruendel, 1986; van der Meer, Beyer, Heinze, & Badel, 2002).

On the other hand, there is very limited evidence on the representation of time’s arrow within individual events (Zwaan, Madden, & Stanfield, 2001). Adopting the framework proposed by Freyd (1987, 1992) and Barsalou (1999), time’s arrow should not only be coded in mental representations as a connection between events, but also in the mental representation of individual events. The event shrinking shall serve as an example. Shrinking is a temporally unidirectional event. An object is related to the event shrinking. Among others, the object is characterized by the opposing features large – small. That is, the event shrinking refers to an object changing from large to small. This transformation might imply temporal order information. This was the starting point for the present study. According to Freyd (1987, 1992), mental representations of real-life events have an inherent time component, making them dynamic representations. This internal temporal dimension is directional, like external time. Thus, items with a temporal orientation toward future time (e.g., shrinking – small) are expected to be processed faster and with higher accuracy than items with a temporal orientation toward past time (e.g., shrinking – large). The first aim of the present study was to test this hypothesis. A relatedness judgment task was used. Participants had to decide whether probe-target pairs were related. The probe was a verb naming an event (e.g., shrinking), whereas the target named a feature of an object related to the event (e.g., small). Relatedness of probe and target was assumed when the target was a feature that correctly characterized the event. For related items, the temporal orientation between probe and target was varied: It could either correspond to the chronological orientation (chronological items, e.g., shrinking – small) or to the reverse temporal orientation (reverse items, e.g., shrinking – large).

In addition, the time interval between the presentation of the probe and the presentation of the target (stimulus onset asynchrony, SOA) was varied: 250 ms versus 1,000 ms. Characteristic time constants for automatic spreading activation mechanisms are a mere 200-250 ms (Fischler & Goodman, 1987; Neely, 1977). If the SOA is considerably longer, strategic processes can modify results of automatic activation (Neely, 1991). A frequently used SOA that enables strategic processing is 1,000 ms. In probe-target paradigms, SOA effects do not strictly argue for either automatic activation or controlled access to mental representations (cf., van der Meer et al., 2002). However, compared with priming tasks, recognition procedures provoke elaborate, semantic processing of information and are considered to be a more direct method of measuring how memorable mental representations are (Gernsbacher & Jescheniak, 1995). For that reason, the recognition procedure was used in the current experiment.

Pupillometrics

A second aim of the study was to support behavioral data, that is, reaction times (RTs) and error rates, with psychophysiological data. The pupillary response proved to be a sensitive, reliable, and consistent measure of the processing load induced by a task, or – more broadly defined – resources allocated to a task (cf., Beatty & Kahneman, 1966; Beatty & Lucero-Wagoner, 2000; Goldwater, 1972; Hess & Polt, 1964; Loewenfeld, 1993). The following rule applies: The more difficult a task is or the more complex a cognitive process is, the more the pupil dilates. Like eye movements (see Rayner, 1998), pupillary movements are a good index of moment-to-moment on-line processing activities. Different aspects of cognitive activity have been successfully investigated using the pupillary response during the last decade: language processing (Hyönä, Tommola, & Alaja, 1995; Just & Carpenter, 1993), perception (Verney, Granholm, & Dionisio, 2001), memory performance (Granholm, Asarnow, Sarkin, & Dykes, 1996; van der Meer, Friedrich, Nuthmann, Stelzel, & Kuchinke, 2003), and attention (Kim, Barrett, & Heilman, 1998).

For the current study, the following global hypothesis holds: Processing of reverse items consumes more resources than processing of chronological items. To test this hypothesis, peak dilation and latency to peak were determined as parameters of the pupillary response. For reverse items, these parameters were expected to have higher values than for chronological items.

Principal Component Analysis (PCA) of Pupillary Responses

In addition, the current study had a third, methodological aim motivated by an apparent paradox in pupillometric research (cf., Schluroff et al., 1986): On the one hand, pupillary movements are considered to be a reliable physiological index of resource consumption. On the other hand, typical measures of the pupillary response are comparatively unidimensional. Thus, the question arises how to compress and analyze all the information represented by a pupillary response. In event-related brain potentials (ERP) research, PCA in combination with analysis of variance (ANOVA) has proven to be meaningful and successful (Donchin & Heffley, 1978). The advantage of PCA for the evaluation of pupillary responses lies in the fact that all information of the pupil data is taken into consideration rather than that of single data points. To further investigate the usefulness of PCA in pupillometric research, we subjected averaged pupillary responses to PCAs (cf., Granholm & Verney, 2004; Schluroff et al., 1986; Siegle, Granholm, Ingram, & Matt, 2001; Siegle, Steinhauer, & Thase, 2004; Verney, Granholm, & Marshall, 2004). We expected to identify a component reflecting the distinct processing demands associated with chronological and reverse items. As for the time course of the pupillary response waveform, the difference in processing chronological and reverse items was expected to appear in a rather late processing stage associated with decision processes.

Method

Participants

Ninety-six psychology students of Humboldt University in Berlin participated in the experiment. They received either course credit or DM 10 payment for their participation. All of them had German as their mother tongue. Twenty students (17 females and 3 males; mean age: 26.1 years) participated in a first pretest to generate the experimental materials and to examine its adequacy. Twenty students (13 females and 7 males; mean age: 24.3 years) participated in a second pretest to examine the temporal relatedness of items. Twenty students (12 females and 8 males; mean age: 26.3 years) participated in a post-hoc free association study to explore the association strength between probe and target which is assumed to indicate the general semantic relatedness of the experimental materials (Strube, 1984). Thirty six students participated in the main experiment. Six participants had to be excluded from all analyses because of technical difficulties. For the main experiment, the final sample consisted of 30 students (21 females and 9 males; mean age: 24.7 years). Students could only participate in one of these studies.

Stimuli & Materials

In a first pretest, participants had to generate verbs that described individual events. Additionally, they were asked to produce pairs of adjectives that are highly familiar past- and future-oriented characterizations of the previously generated events (e.g., shrinking: large – small). In total, participants generated 136 different triplets. These triplets were examined in a second pretest. Participants were presented with a verb (e.g., shrinking) describing a change in time. The verb was accompanied by a pair of adjectives or participles (e.g., large – small). Participants had to rate on a 5-point scale (from 1 = very bad to 5 = very good) how well the word pair reflected the change in time. The rating was assumed to show how well the word-pair was able to depict changes in persons or objects, associated with a specific event. Those triplets (individual event and feature-pair) that reached a median of at least four on the rating scale were selected. Next, highly emotional as well as especially short or long triplets were excluded. The remaining triplets were believed to best represent the temporal directionality of real-life events. The chronological and reverse items (i.e., related items) were constructed in the following way: For chronological items, an individual event was combined with its future-oriented feature (e.g., steaming – tender). For reverse items, an individual event was combined with its past-oriented feature (e.g., shrinking – large) (see Appendix).

Because the temporal relationship is a special case of semantic relationship, we intended to control the experimental materials for global semantic relatedness, too. In a post-hoc free association study, the participants were presented with the probes (e.g., shrinking) and were asked to utter the first words that came to mind. All free associations that were generated within 10 s were recorded. For every participant and every related item, four binary scores (yes vs. no) were determined, scoring 1 as 'yes' and 0 as 'no': (1) Was the first associative response to the presented probe the target word? (2) Was the first response a word similar to the meaning of the target (e.g., a synonym)? (3) Was the target word within the top five responses to the probe? (4) Was a word similar to the target within the first five responses? Next, 4 association strength measures were computed. For score (1), for example, the association strength between probe and target was calculated by the number of participants whose first response was the target word, divided by the total number of participants. Thus, the strength of association between the two words is represented by a number between 0 and 1. Of course, this association measure exhibits the lowest mean probe-target association frequencies (chronological items: 0.09; reverse items: 0.07) while score (4) shows the highest values (chronological items: 0.24; reverse items: 0.19). These free association findings correspond with results reported in the literature (see Strube, 1984, for a complex review). For verbs, adjectives are associated with low frequency and rather late in the association sequence. For statistical analysis, we used the mean of the four association strength measures as a combined measure. A 2 (SOA 250 vs. 1,000 ms) × 2 (temporal orientation: chronological vs. reverse items) item ANOVA yielded no significant effects (SOA: $F(1,36) = 0.180$, $MSE = 0.021$, $p = .674$, $\eta^2 = .005$; temporal orientation: $F(1,36) =$

0.744, $p = .394$, $\eta^2 = .020$; SOA × temporal orientation: $F(1,36) = 1.419$, $p = .241$, $\eta^2 = .038$).[1] Thus, probe-target association frequency is equal for the experimental item groups.

The main experiment consisted of two item blocks, each containing 12 practice and 40 test items. Each item was composed of the probe (e.g., shrinking) and the target (e.g., large). 50 % of the items were related (e.g., shrinking – large), the remaining 50 % of items were unrelated (e.g., shaving – far). For related (i.e., experimental) items, the temporal orientation between probe and target could either correspond to the chronological order (e.g., steaming – tender), in which case the items were referred to as chronological items. Or, it could run against the chronological order, in which case the items were referred to as reverse items (e.g., shrinking – large). The chronological and reverse item groups were also controlled for the number of letters (for probes, mean = 8.1 letters, for targets, mean = 5.2 letters) and word frequency (for probes, mean = 16.5 occurrences/million; for targets, mean = 248.1 occurrences/million; CELEX database; Baayen, Piepenbrock, & Gulikers, 1995).

The unrelated probe-target pairs (filler items) were constructed by using the same 40 individual events as for the related items (see Appendix). They were combined with features that had occurred in the unused triplets. Thus, in the main experiment every individual event (probe) appeared twice: In one item block it was part of a related item whereas in the other item block it was part of a filler item. Because the block order was switched between participants, the word repetition was not supposed to have a confounding effect.

The experiment was run in German. All examples have been translated into English. The original materials, both in German and English, are presented in the Appendix.

Design

The following independent variables were considered in the experiment (within subjects): SOA (250 ms and 1,000 ms) and temporal orientation (chronological and reverse). The participants were presented half of the items with an SOA of 250 ms (Block 1) and the other half with an SOA of 1,000 ms (Block 2). The block order was switched between participants, who were randomly assigned to one of the two versions. Probe and target were either related (50%) or unrelated (50%). For related items, the temporal orientation between probe and target was varied: either corresponding to chronological order (50%; e.g., steaming – tender) or reverse order (50%; e.g., shrinking – large). Unrelated items (i.e., filler items) had no meaningful relation (neither temporal order nor global semantic relation) between probe and target (e.g., shaving – far). These filler items were included in the experiment so that participants would not only be exposed to related items. No hypotheses were made regarding the processing of filler items. Still, they were included in some exploratory analyses. Within an SOA condition, items were presented randomly.

The following dependent variables were recorded: reaction times (RTs), error rates, and pupillary responses.

Procedure

The experiment took place in a quiet medium illuminated room (background luminance = 500 lux). The participants received written instructions. They were seated comfortably in front of a computer monitor with the chin and forehead stabilized in a headrest. Seating height could be adjusted to the participant's height. The headrest was used to reduce movement artifacts and to maintain a distance of 100 cm between the participant's eye and the computer monitor.

Every trial consisted of five phases. The trial started with a fixation cross which was presented for 1,500 ms (baseline phase). Then, the probe was presented for either 250 or 1,000 ms followed by the target. Participants had to decide as quickly and accurately as possible whether there was a meaningful relationship between probe and target. If there was, they were instructed to press a right external button; if there was not, they were to press a left external button. The target disappeared from the screen as soon as the key was hit. A pupil relaxation phase of 2,000 ms followed. The trial ended with a blinking phase of variable duration. The participants could start the next trial by pressing one of the two keys.

Participants were also asked not to move their head, to maintain fixation, and to restrict eye blinks – if possible – to the so-called blinking phase at the end of the trial. After the experiment, participants filled out a questionnaire that ascertained demographic data as well as factors that are known to affect pupil dilation (Loewenfeld, 1993).

Apparatus

Pupillometry was done with an iView system (SensoMotoric Instruments) and an IBM-compatible microcomputer for stimulus presentation using the software Experimental Run Time System (version 3.19). The iView system consists of a video camera that is sensitive to infrared light, an infrared light source that was pointed at the participant's eye, and a device that tracks size and location of the pupil. Pupil diameter was sampled at 50 Hz. Working with visual stimuli demands special conditions of the experimental setting. It is necessary to control the confounding effect of the initial light reflex reaction (Loewenfeld, 1993; Steinhauer & Hakerem, 1992). As mentioned above, the number of letters was balanced for the experimental conditions. This was done to keep reading times constant and to assure that the luminance of the display did not systematically differ between the conditions. The pupil diameter is not affected by color, but by luminance levels. In the present study, the stimuli were presented in red on a black screen, ensuring that the change in luminance was rather small (Zimmer, 1984), but with sufficient legibility. The luminance of the stimuli was on average 5 cd/ m^2.

The iView system measured pupil diameter in terms of pixels. To relate this measure to absolute pupil size, a calibration procedure was employed. At both the beginning and the end of the experiment, a black dot being 5 mm in diameter was placed on the closed lid of the participant's right eye. The pupillometer determined the size of this artificial pupil in terms of pixels. This procedure made it possible to convert pupil diameter from pixels to millimeters for each participant.

Data Selection, Cleaning, and Reduction

False responses were excluded from RTs analyses and pupil data analyses. The distribution of RTs of all remaining items was determined. Trials with RTs less than 300 ms and greater than 2,000 ms were excluded from analyses. This procedure eliminated less than 2 % of the relevant trials.

As for pupil data, graphic displays of the raw pupil diameters were first checked visually for gross artifacts. Across all participants, very few trials (less than 1%) had to be discarded due to loss of measurement or excessive blinking. Outliers and pupillary artifacts were not systematically distributed across experimental conditions. A computer algorithm was developed to remove complete and partial eye blinks as well as other minor artifacts from other trials. Blinks were defined as large changes in pupil diameter occurring too rapidly to signify actual pupil dilation or constriction. Linear interpolation was used to correct blinks. Data were not smoothed. For every trial, the average pupil diameter of the 200 ms preceding the probe onset was subtracted from the pupil diameter after probe presentation to produce pupil dilation difference score indices (baseline correction). For each participant and for each of the experimental conditions, an average target-locked pupillary response was then calculated for all artifact-free trials. These were then averaged across participants. Following Beatty & Lucero-Wagoner (2000), two parameters were calculated to characterize the pupillary response: peak dilation, and latency to peak. Peak dilation was defined as the maximal dilatation obtained in the measurement interval of interest. This measure has the advantage of being independent of the number of data points occurring in the measurement interval (Beatty & Lucero-Wagoner, 2000). Latency to peak refers to the amount of time between start of the measurement interval and emergence of the peak dilation. Computation of pupil parameters was not based on individual trials, but on the average pupillary response for each participant in each condition (cf., Granholm et al., 1996; Verney et al., 2004). Averaging across a certain number of trials is necessary because the pupil response is prone to spontaneous fluctuations. In the present study, an average pupil response was based on a minimum of 6 trials (maximum: 10 trials, mean: 9.1 trials), which proved to be sufficient for a reliable peak picking. In addition, averaged probe-locked pupillary responses were submitted to PCAs. All participant-based analyses were run on means obtained for each participant in each condition. An alpha level of .05 was used for all statistical analyses.

Behavioral Results and Discussion

Reaction Times and Error Rates

Descriptive evidence is displayed in Table 1 and includes the means (M), and standard errors (SE) of RTs, and error rates. Since the hypotheses about time's arrow refer to the related items, the filler items were only included in some exploratory analyses reported below.

Insert Table 1 about here

A 2 (SOA: 250 vs. 1,000 ms) × 2 (temporal orientation: chronological vs. reverse) repeated measures analysis of variance (ANOVA) was performed.

RTs. The analysis revealed a statistically significant main effect of both SOA [$F(1,29) = 10.77$, $MSE = 25{,}788$, $p = .003$, $\eta^2 = .271$] and temporal orientation [$F(1,29) = 48.41$, $MSE = 6{,}662$, $p = .000$, $\eta^2 = .625$]. The interaction SOA × temporal orientation was not significant [$F(1,29) = 1.45$, $MSE = 4{,}475$, $p = .238$, $\eta^2 = .048$]. Thus, our data support the hypothesis that items with a temporal orientation toward future time are processed faster than items with a temporal orientation toward past time.[2]

Error Rates. The analysis of error rates revealed a significant temporal orientation effect for the 1,000-ms SOA condition [$\chi^2 (0.05;1) = 15.308$, $p = .000$] with fewer errors for chronological items than for reverse items. For the 250-ms SOA condition, the mean error rates were equal for chronological and reverse items [χ^2 (0.05;1) = 0, p = 1.0]. Importantly, error rates indicated that there was no speed-accuracy trade-off in the data.

Pupillometric Results and Discussion

Pupillary responses were time-locked to the onset of target presentation, and to the onset of probe presentation; both averaging methods correspond to stimulus-locked averaging.

Target-Locked Averaging

For target-locked averaging, a constant time window was chosen: 2,300 ms onwards from target presentation. Peak dilation and latency to peak were computed across the entire 2,300 ms window. Mean pupillary responses, averaged across all 30 participants, are shown in Figure 1A.

Insert Figure 1 about here

Descriptive statistics are displayed in Table 2 and include means (M), and standard errors (SE) for the pupil parameters latency to peak, peak dilation, and baseline pupil diameter.

Insert Table 2 about here

For related items, a 2 (SOA: 250 vs. 1,000 ms) × 2 (temporal orientation: chronological vs. reverse) repeated measures ANOVA for every pupil parameter was performed.

Latency to peak. Latency to peak runs parallel to RTs: There were significant main effects for both SOA [$F(1,29) = 4.22$, $MSE = 218{,}698$, $p = .049$, $\eta^2 = .127$] and temporal orientation [$F(1,29) = 14.72$, $MSE = 55{,}261$, $p = .001$, $\eta^2 = .337$] with the interaction SOA × temporal orientation being not significant [$F(1,29) = 0.06$, $MSE = 53{,}571$, $p = .814$, $\eta^2 = .002$].

Peak dilation. There was a significant main effect for temporal orientation [$F(1,29) = 6.14$, $MSE = 0.00476$, $p = .019$, $\eta^2 = .175$] whereas the other effects were not significant [SOA: $F(1,29) = 2.32$, $MSE = 0.00959$, $p = .139$, $\eta^2 = .074$; SOA × temporal orientation: $F(1,29) = 1.37$, $MSE = 0.00500$, $p = .251$, $\eta^2 = .045$].

Taken together, pupil data confirm the results from the RTs analysis. For both SOA conditions, the processing of reverse items consumes more resources than the processing of chronological items. Higher processing load is reflected in higher peak dilation and longer latency to peak.

Interdependence of Pupillary and Behavioral Measures

Our data confirm the existence of a significant correlation between latency to peak and peak dilation for all four relevant conditions (chronological items, 250-ms SOA: $r = .690$; reverse items, 250-ms SOA: $r = .565$; chronological items, 1,000-ms SOA: $r = .513$; reverse items, 1,000-ms SOA: $r = .450$). The correlation between latency to peak and RTs was also significant in all conditions (chronological items, 250-ms SOA: $r = .365$; reverse items, 250-ms SOA: $r = .567$; chronological items, 1,000-ms SOA: $r = .550$; reverse items, 1,000-ms SOA: $r = .392$). However, the correlation between RTs and peak dilation was significant for the 250-ms SOA condition only (chronological items: $r = .479$; reverse items: $r = .485$). At the same time it becomes clear that the joint consideration of both peak dilation and latency to peak is warranted. It appears that peak dilation reflects resources allocated to a task while latency to peak, like reaction time, is a speed parameter.

Examination of Possible Confounds

Baseline pupil diameter. According to the standard to quantify pupillary responses (Beatty & Lucero-Wagoner, 2000), baseline pupil diameter for experimental conditions is displayed in Table 2. The available evidence indicates that the extent of the pupillary dilation evoked by cognitive processing is "independent of baseline pupillary diameter over a physiologically reasonable but not extreme range of values" (Beatty, 1982, p. 284 with further references). Interestingly, results by Hoeks & Ellenbroek (1993) demonstrated that this independence from baseline holds for baseline values smaller than 7 mm only. In the current study, there were significant individual differences in baseline pupil diameter (range: 2.18 - 7.56 mm). However, in 98% of all trials, baseline pupil diameter was smaller than 7 mm. Still, as a control analysis, a 2 (SOA) × 2 (temporal orientation) repeated measures ANOVA was employed and revealed no significant effects (all Fs < 2.01).

Blocked presentation of SOA conditions. Further control analyses examined to what extent the blocked presentation of SOA conditions affected the data. For that reason, "starting SOA" (250 vs. 1,000 ms) was added as a between-subjects factor to the SOA × temporal orientation repeated measures ANOVA with RTs, peak dilation, and latency to peak being dependent variables in separate analyses. The analyses revealed that the blocked presentation of SOA conditions did not affect the data in a confounding way. Most importantly, ANOVAs for all three measures revealed no significant effect for "starting SOA" (all Fs < 2.11).

Influence of light reaction. To examine the influence of the light reaction, pupillary responses were averaged time-locked to the presentation of the probe (Figure 1B). The zero value on the x-axis (= time axis) represents the time point of target presentation. The presented pupillary response waveforms are bimodal. Following the visual presentation of the probe, there is an initial pupil constriction in terms of a light reaction. It is followed by a redilation and an additional dilation reflecting the processing of the experimental stimulus. The data indicate that the probe-induced light reaction was noticeably weakened in the short

SOA condition, due to the early presentation and processing of the target. Compared to the long SOA condition, the constriction amplitude is reduced and the redilation goes faster (Klix, van der Meer, & Preuß, 1985; Verney et al., 2001). Still, it remains debatable to what extent the differences in probe duration hamper the comparison of pupil response parameters, based on target-locked averaging, for the two SOA conditions. For a control analysis, a second baseline was established, defined as the average across the last 60 ms before target presentation. A 2 (SOA: 250 vs. 1,000 ms) × 2 (temporal orientation: chronological vs. reverse) repeated measures ANOVA revealed no significant effects (all Fs < 1.1). Thus, the baseline pupil diameter at the start of the target presentation is not significantly different for the experimental conditions. However, Figure 1B reveals that the mean pupillary response movement (i.e., increasing, decreasing, stable) at the start of target presentation is different for the two SOA conditions: While the averaged curves for the short SOA condition show that the pupil is still in the constriction phase, the averaged pupillary responses for the 1,000-ms SOA condition indicate that the pupil is already at the beginning of the redilation phase. This inconsistency might be responsible for the lacking SOA effect on peak dilation.

However, it should be emphasized that the discussed issue of differences in probe duration does not undermine the main focus of the paper which is the examination of mental coding of time's arrow. The manipulation of temporal orientation within each SOA condition is not affected by differences in probe duration: All parameters (i.e., RTs, latency to peak, and peak dilation) reflect the influence of temporal orientation of items on relatedness judgments.

Exploratory Analyses of Filler Items

As mentioned in the Methods section, no predictions were made concerning the processing of filler items. For exploratory reasons only, a global analysis of filler items was performed. Analysis of filler vs. related items required a different splitting of the data. For each SOA condition, the 10 chronological and 10 reverse items were pooled (n = 20 related items) and contrasted with the 20 filler items (unrelated items). First, the error rates for filler items were low (SOA 250 ms: 2.7%; SOA 1,000 ms: 3.0%). This finding supports the validity of the filler items: Participants had no difficulty in rejecting filler items as unrelated probe-target pairs. Figure 2 displays mean pupillary responses, time-locked to probe presentation, as well as mean RTs. Note: All results for related items necessarily represent the same data as the main analysis of time's arrow, yet giving up the differentiation between chronological and reverse items.

Insert Figure 2 about here

For RTs, latency to peak, and peak dilation as dependent variables in separate analyses, 2 (relatedness: related vs. unrelated) × 2 (SOA: 250 vs. 1,000 ms) repeated measures ANOVAs were performed. Peak dilation proved to be the only measure showing a significant relatedness effect with higher peak dilations for related items than for unrelated items [$F(1,29) = 10.34$, $MSE = 0.004$, $p = .003$, $\eta^2 = .263$]. In addition, peak dilation showed a significant effect of SOA [$F(1,29) = 4.22$, $MSE = 0.006$, $p = .049$, $\eta^2 = .127$] with higher peak dilations for the 1,000-ms SOA condition than for the 250-ms SOA condition. For latency to peak, the SOA effect failed to be significant [$F(1,29) = 2.74$, $MSE = 115{,}372$, $p = .109$, $\eta^2 = .086$]. RTs clearly exhibited a significant effect of SOA [$F(1,29) = 10.68$, $MSE = 20{,}661$, $p = .003$, $\eta^2 = .269$] with longer RTs for the 1,000-ms SOA condition compared with the 250-ms SOA condition.

Analysis of error rates revealed a significant relatedness effect for both SOA conditions [SOA 250 ms: $\chi^2(0.05;1) = 11.83$, $p = .001$; SOA 1,000 ms: $\chi^2(0.05;1) = 12.22$, $p = .001$] with mean error rates being significantly higher for related compared to unrelated items.

Taken together, pupillary responses indicated that more processing resources were consumed for related than for unrelated items.

Principal Component Analysis (PCA)

To identify unique components of individuals’ pupil responses in the relatedness judgment task, participant’s averaged pupil dilation waveforms in each relevant condition were subjected to a PCA. In order to better account for the differences in probe duration, the PCA was based on probe-locked rather than target-locked averaged pupillary responses. Therefore, a separate PCA was employed for each SOA condition.

In PCA, pupil measures at each point in time are considered to be dependent variables (cf., Donchin & Heffley, 1978). PCA, followed by an analytic rotation, was used as a technique for extracting a small number of factors, each representing systematic influences on many points in time, from the total variance in the pupillary response time × person/condition matrix. Thus, factors represent groups of points in time with high bivariate correlations. Varimax rotation was used to concentrate the high loadings for each factor to a restricted region of the pupillary waveform, thereby producing distinct basic components (cf., Donchin & Heffley, 1978).

For the 250-ms SOA condition, five factors with eigen-values over one were extracted. A Scree plot revealed differences between the first three factors and the rest. The first three factors, accounting for 96.08% of the total variance, also met the criteria proposed by Guadagnoli and Velicer (1988). The authors suggest that a factor can be interpreted if at least four variables load higher than .60 on the factor or if at least 10 variables have loadings higher than .40. Similarly, for the 1,000-ms SOA condition, 6 factors had eigen-values over one. Again, three of them were distinguishable on a Scree plot and fulfilled the loading criterion. They accounted for 91.12% of the variance. Therefore, a second PCA was performed for each SOA condition, limiting extraction to three factors only (cf., Siegle et al., 2001). Table 3 (upper half) presents the obtained factor structures. The factors are ordered and numbered according to the time course of the pupillary response. The chronological order of factors is reflected in the latencies to peak loading, which are also presented in Table 3. Note that zero represents the moment of target presentation; thus, negative values represent the SOA phase where the probe was presented while positive values reflect the period of time after target presentation.

Insert Table 3 about here

The results of a PCA can generally be interpreted by examining factor loadings and factor scores. A factor loading is a correlation between a factor and a variable (Donchin & Heffley, 1978). Factor loadings are used to describe different components of the pupillary response. In Figure 3, they are graphically depicted.

Insert Figure 3 about here

Factor loadings are specific to variables. Their statistical examination would not allow differentiation between chronological and reverse items. Therefore, factor loadings were used as sets of weights to compute factor scores for each participant, and experimental condition. Factor scores are z-standardized values. Table 3 (lower half) presents the means (M), and standard errors (SE) of factor scores. For every PCA factor, factor scores were submitted to a one-factorial repeated measures ANOVA with temporal orientation (chronological vs. reverse) as within-participants factor. As can be seen in Figure 3, each factor is characterized by a single distinct rise, peak, and fall in loadings. Figure 3 has to be interpreted together with Figure 1B. In both figures, the x-axis is the time axis representing the time window used for probe-locked averaging of pupillary responses.

For the 1,000-ms SOA condition, the first factor is loading at the beginning of the waveform. This early factor has high loadings during the whole SOA phase. It is assumed to reflect the pupil constriction in response to the visually presented probe as well as the perception and processing of the probe. The manipulation of temporal orientation did not significantly affect this early factor [$\underline{F}(1,29) = 3.98$, $\underline{MSE} = 0.518$, $\underline{p} = .055$, $\eta^2 = .121$]. The following factor has its highest loadings during presentation of the target. This factor is assumed to mirror the redilation and further dilation of the pupil which indicates resource consumption due to processing of the target. Again, the factor was not significantly affected by temporal orientation [$\underline{F}(1,29) = 0.13$, $\underline{MSE} = 0.276$, $\underline{p} = .725$, $\eta^2 = .004$]. Finally, the third factor represents the point in time where the pupil curves for chronological and reverse items, respectively, diverge. For interpretation on the time scale, the latency of the pupillary response has to be taken into consideration: The pupil dilation is characterized by a lag of 300-500 ms following the stimulus (Loewenfeld, 1993). Thus, the third factor is associated with the period before and after the (latency-corrected) behavioral reaction. This suggests that the factor mainly reflects decision processes on the relatedness between probe and target as well as processes of motor response selection and execution. The late factor also reflects the pupil's natural tendency to return to baseline following the response. As hypothesized, the late factor was significantly affected by temporal orientation [$\underline{F}(1,29) = 13.49$, $\underline{MSE} = 0.337$, $\underline{p} = .001$, $\eta^2 = .317$] with a positive mean factor score for reverse items and a negative mean factor score for chronological items. Thus, participants' pupillary responses were more distinct for reverse than for chronological items.

There is a slightly different picture for the 250-ms SOA condition. The first factor is loading at the beginning of the waveform, peaking 120 ms after presentation of the target. The factor has high loadings until the mean reaction time is reached. Taking into account this long-lasting influence, the early factor is assumed to reflect different processes, which temporally overlap or run in parallel: the light reflex elicited by the visually presented stimuli, processing of the probe and the beginning of processing the target. The middle factor supports this idea: Compared to the middle factor in the 1,000-ms SOA condition, it exhibits rather low loadings and accounts only for 12% of the variance. The points in time that are associated with the middle factor are also associated with the early and/or late factor, respectively. Thus, the middle factor is assumed to reflect the continual processing of the target. Most importantly, as with the long SOA condition, there is a late factor that is associated with the period before and after the (latency-corrected) behavioral reaction. Again, the late factor is the only factor significantly affected by temporal orientation [$F(1,29) = 7.48$, $MSE = 0.207$, $p = .011$, $\eta^2 = .205$]. Thus, it is assumed to reflect the relatedness decision as well as processes of motor response selection and execution.

General Discussion

A psychophysiological measure, namely the pupillary response, was used combined with behavioral measures, RTs and error rates, on a probe-target paradigm to investigate whether time's arrow is mentally coded. The study yielded four main findings. First, consistent with the hypotheses, items with a temporal orientation toward future time were processed faster than items with a temporal orientation toward past time; this holds for both SOA conditions. Second, the pupil data supported the behavioral data. They confirmed the global hypothesis that the processing of reverse items consumes more resources than the processing of chronological items. Third, results of PCAs showed that the pupil waveforms of chronological and reverse items diverged significantly from each other, within a certain period. As hypothesized, this difference appeared in a late processing stage associated with decision processes. In this respect, PCA provided additional information about the time course of information processing. Fourth, results of PCAs were supplemented by the additional analysis of distinct parameters of the pupillary response. Both peak dilation and latency to peak showed a significant temporal orientation effect.

The experiment was motivated by three central questions. The first question was whether time's arrow is also mentally coded in individual events. The results indicated that reverse items led to increased RTs compared to chronological items. This finding points to the sensitivity of humans to temporal directionality in individual real-life events. Taking into account the evidence for time's arrow found in experiments with routine event sequences (cf., Krüger, 2000; van der Meer et al., 2002) or visually presented gravity stimuli (Friedman, 2002), the results presented here provide a demonstration of a robust effect of temporal directionality in general event knowledge. Freyds (1987, 1992) emphasis on a directional temporal dimension in the mental representation of the external world provides a context for this finding. In addition, our results support Barsalou's (1999) view that mental event representations preserve aspects of the initial perceptual and experiental input. As for theoretical explanations of psychological processes underlying the sensitivity of humans to temporal directionality in real-life events, Grafman (1995) proposed an association strength account. The more frequently a special event order is carried out in real life, the more time's arrow is established in memory, and the lower is the threshold for its activation. In the present experiment, we analyzed the mental coding of time's arrow in <u>individual</u> <u>events</u>. We did control chronological and reverse items for temporal relatedness and association frequency. Importantly, the results of an ANCOVA showed that association frequency was not responsible for the obtained temporal orientation effect. Thus, the association strength account cannot be the only explanation for the temporal orientation effect (cf., Krüger, 2000; van der Meer et., 2002). Psycholinguistic research has proposed that the default assumption of comprehenders is that the order in which events are reported in language corresponds to their chronological order. This has been called the iconicity assumption (Fleischman, 1990; Zwaan, 1996; van der Meer et al., 2002). For the present study, the iconicity assumption can be regarded as a top-down or strategy-driven influence on probe-target processing. If the iconicity assumption is confirmed, the decision about the relatedness between probe and target is facilitated. Chronological items fit this criterion. For reverse items, however, the assumption is not confirmed leading to longer reaction times.

What do the results of our study tell us about when people apply the iconicity assumption in relatedness judgments? There are two possibilities: On the one hand, it could be applied online while processing the probe. If this was the case, an SOA of 1,000 ms should be helpful in speeding up and improving the recognition of chronological items compared with an SOA of 250 ms. On the other hand, it is possible that the iconicity assumption affects performance offline while checking the target against the probe. Then, the long SOA interval should not facilitate the recognition of chronological items, compared to the short SOA interval. The RT data and the results of PCAs on pupil data support the second view. They point to a rather late influence of temporal orientation on relatedness judgments. Interestingly, the error rates point to an earlier influence of the iconicity assumption. For the 250-ms SOA interval, the error rates did not differ between chronological and reverse items. For the 1,000-ms SOA interval, however, reverse items led to higher error rates as compared to chronological items. Presumably, the long SOA interval allowed for strategic processes (Gernsbacher & Jescheniak, 1995) leading to an elaborative construction of word meaning (Kintsch, 1998). Following the iconicity assumption, future-oriented features might be partly predicted. In consequence, the recognition of chronological items is improved. The recognition of reverse items, however, is hampered leading to a higher error rate for reverse items which are erroneously rejected as “unrelated”.

The second question that motivated the present research was whether pupillary responses supported and extended behavioral findings. All parameters tested, namely RTs, latency to peak, and peak dilation, reflected the influence of temporal orientation of items on relatedness judgments. The behavioral responses indicate speed and accuracy of processing. The pupil data, however, add something unique to the behavioral data: They indicate resources allocated to the task and the specific time-course of task-processing.

The third question that motivated the present experiment was whether PCA could provide additional evidence concerning distinct components reflecting differences in processing chronological and reverse items. For each SOA condition, PCA yielded a significant temporal orientation effect for the factor accounting for variance mostly around and after the (latency-corrected) reaction time. This factor also shows relevant loadings before the reaction time. Thus, it seems reasonable to relate this factor to the decision-making about the relatedness between probe and target. Taking into account the iconicity assumption discussed above, the decision process should consume more resources for reverse items as compared to chronological items. As was hypothesized, the factor sensitive to the temporal orientation manipulation was a late factor. This seems to be in line with findings from other pupillometric studies. For example, Verney et al. (2001, 2004; see also Granholm & Verney, 2004) attributed a late factor to attentional processes that consume more resources than to earlier perceptual identification processes. Siegle et al. (2001) attributed an even later component to effortful depressive ruminations. A strength of the PCA is that it standardizes the pupil response for each individual by taking out the individual differences in the magnitude of a response. As becomes evident from the reported study, the interpretation of PCA factors in terms of components of information processing is not easy. The attribution of specific processes to the extracted factors needs to be confirmed by future research, for example, by manipulating decision making load or response selection load and determining the impact of these manipulations on PCA results.

In conclusion, the present experiment suggests that time's arrow is mentally coded in individual real-life events. Our results add to the literature concerning the sensitivity of humans to temporal directionality, which has been studied in the context of highly familiar sequences of events (cf., Grafman, 1995; Krüger, 2000), visually presented gravity stimuli (Friedman, 2002), children's intuitive understanding of entropy (Friedman, 2001), and temporal order relations in language comprehension (van der Meer et al., 2002; Zwaan, 1996). A broader implication of the present work is that the psychological arrow of time allows humans to anticipate nonpresent events and to prepare actions in advance. This, in turn, would increase the probability of solving a variety of tasks efficiently. One limitation with this interpretation of the data is that our study focused explicitly on temporal orientability as a basic presupposition of causality. The experimental materials were controlled for temporal relatedness, association frequency (i.e., global semantic relatedness, cf., Strube, 1984), number of letters, and word frequency. Of course, it is possible that properties other than the ones discussed here may further contribute to the decision process. For example, event duration in reality, operativity, necessity, and sufficiency in the circumstances (cf., Trabasso et al., 1989; van der Meer et al., 2002) may have relevance, too. This point should be investigated more systematically in the future.

The combination of the pupillary response, indicating how many cognitive resources are required by an experimental task, with traditional behavioral measures like RTs and error rates, is a powerful approach to study information processing in more detail. The pupillary response proved to be an important psychophysiological reporter variable (Beatty & Lucero-Wagoner, 2000) which in the current study shed light on psychological processes underlying human’s sensitivity to temporal directionality in real-life events.

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Appendix

Word Material, in both German and English

SOA 250 ms Chronological Items	SOA 250 ms Reverse Items	SOA 1,000 ms Chronological Items	SOA 1,000 ms Reverse Items
anschleifen – scharf grinding – sharp	beschmieren – gepflegt besmearing – tidy	aufmuntern – heiter cheering up – happy	abkühlen – heiß cooling – hot
aufräumen – ordentlich tidying – neat	dehnen – eng stretching – tight	auftürmen – hoch piling – high	austrinken – voll drinking up – full
beleuchten – hell illuminating – bright	kleckern – sauber smudging – clean	bremsen – langsam braking – slow	braten – roh frying – raw
dünsten – weich steaming – tender	platzen – prall bursting – plump	entspannen – locker relaxing – laid back	durchwühlen – geordnet rummaging – sorted
knittern – faltig crinkling – wrinkled	saufen – nüchtern boozing – sober	fliehen – frei escaping – free	eingießen – leer pouring in – empty
lüften – frisch airing – fresh	schlafen – müde sleeping – tired	gefrieren – hart freezing – hard	essen – hungrig eating – hungry
rasieren – glatt shaving – smooth	schleifen – rauh sanding – rough	kräftigen – stark strengthening – strong	fönen – feucht blow-drying – damp
renovieren – neu renovating – new	schrumpfen – groß shrinking – large	putzen – blitzblank cleaning – neat	klammern – locker stapling – loose
üben – gut practising – good	schwärzen – hell blackening – bright	regnen – nass raining – wet	korrigieren – falsch correcting – wrong
zunehmen – dick gaining weight – fat	sterben – lebendig dying – alive	verwesen – modrig decaying – fusty	schmelzen – fest melting – solid
SOA 250 ms Filler Items		**SOA 1,000 ms Filler Items**	
aufmuntern – besetzt cheering up – occupied	abkühlen – bewegt cooling – emotional	anschleifen – allgemein grinding – general	beschmieren – getrennt besmearing – separated
auftürmen – verdünnt piling – diluted	austrinken – bebaut drinking up – cropped	aufräumen – spitz tidying – spiky	dehnen – offen stretching – open
bremsen – verderblich braking – noxious	braten – ernst frying – serious	beleuchten – flüssig illuminating – fluid	kleckern – laut smudging – loud
entspannen – geteilt relaxing – divided	durchwühlen – betäubt rummaging – numb	dünsten – feindlich steaming – hostile	platzen – verschwommen bursting – blurred
fliehen – gesund escaping – healthy	eingießen – sonnig pouring in – sunny	knittern – nah crinkling – close	saufen – gasförmig boozing – gaseous
gefrieren – freundlich freezing – friendly	essen – defect eating – defective	lüften – glasig airing – glassy	schlafen – selbstsicher sleeping – confident
kräftigen – launisch strengthening – moody	fönen – wach blow-drying – awake	rasieren – fern shaving – distant	schleifen – entmutigt sanding – discouraged
putzen – salzig cleaning– salty	klammern – matt stapling – dull	renovieren – hohl renovating – hollow	schrumpfen – leise shrinking – quiet
regnen – kompliziert raining – complicated	korrigieren – geschmolzen correcting – melted	üben – schmutzig practising – dirty	schwärzen – krumm blackening – twisted
verwesen – frech decaying – cheeky	schmelzen – weit melting – far	zunehmen – vereist gaining weight – frosted	sterben – stumpf dying – blunt

Author Note

Antje Nuthmann, Department of Psychology, Humboldt University at Berlin (now at University of Potsdam); Elke van der Meer, Department of Psychology, Humboldt University at Berlin.

Correspondence concerning this article should be addressed to Elke van der Meer, Department of Psychology, Humboldt University at Berlin, Rudower Chaussee 18, 12489 Berlin, Germany.

E-mail addresses: vdMeer@rz.hu-berlin.de (E. van der Meer), nuthmann@rz.uni-potsdam.de (A. Nuthmann)

Footnotes

[1]If employed on each of the four single measures, none of the item ANOVAs yielded any significant effects.

[2]A control analysis was performed to test whether the temporal orientation effect was confounded with association strength between probe and target. Association strength data were obtained by item. Therefore, an item analysis on RTs with probe-target association frequency as a covariate was performed. Thus, for each item in each condition (10 items per condition) reaction time data were collapsed across all participants. Since a given item appeared in one condition only, between item variability was considered. The combined association score (see Stimuli & Materials section) had a significant main effect on RTs [$F(1,35) = 13.22$, $MSE = 6{,}536$, $p = .001$, $\eta^2 = .274$]. However, after levelling out the effect of this covariate, there still were significant main effects of SOA [$F(1,35) = 15.54$, $p = .000$, $\eta^2 = .307$] and temporal orientation [$F(1,35) = 11.58$, $p = .002$, $\eta^2 = .249$]. These results suggest that the employed experimental manipulation was a valid test of time's arrow.

Table 1

Means (M), and Standard Errors (SE) of Reaction Times, and Error Rates Dependent on SOA and Temporal Orientation (Upper Half) or Relatedness (Lower Half)

SOA	250 ms		1,000 ms	
Temporal Orientation	Chronological	Reverse	Chronological	Reverse
	Reaction Times			
M (ms)	741	860	852	941
SE (ms)	33	39	41	40
	Error Rates			
RF (%)	6.0	6.0	3.7	12.3
Relatedness	Related (Correct Items)	Unrelated (Filler Items)	Related (Correct Items)	Unrelated (Filler Items)
	Reaction Times			
M (ms)	801	820	894	898
SE (ms)	35	32	39	38
	Error Rates			
RF (%)	6.0	2.7	8.0	3.3

RF: relative frequency.

Table 2

Means (M), and Standard Errors (SE) for Different Pupil Parameters Dependent on SOA and Temporal Orientation (Upper Half) or Relatedness (Lower Half)

SOA	250 ms		1,000 ms	
Temporal Orientation	Chronological	Reverse	Chronological	Reverse
	Latency to Peak			
M (ms)	1,100	1,275	1,285	1,440
SE (ms)	86	68	67	77
	Peak Dilation			
M (mm)	0.196	0.212	0.208	0.255
SE (mm)	0.023	0.024	0.021	0.022
	Baseline Pupil Diameter			
M (mm)	4.587	4.643	4.602	4.627
SE (mm)	0.166	0.154	0.161	0.163
Relatedness	Related (Correct Items)	Unrelated (Filler Items)	Related (Correct Items)	Unrelated (Filler Items)
	Latency to Peak			
M (ms)	1,229	1,225	1,324	1,335
SE (ms)	66	54	59	64
	Peak Dilation			
M (mm)	0.195	0.158	0.222	0.187
SE (mm)	0.022	0.016	0.019	0.016
	Baseline Pupil Diameter			
M (mm)	4.617	4.623	4.614	4.609
SE (mm)	0.156	0.157	0.160	0.156

Table 3

Principal Component Analysis on Pupil Data for Meaningfully Related Probe-Target Pairs; Separate Analyses of Both SOA Conditions. Obtained Factor Structure as well as Means (M), and Standard Errors (SE) of Factor Scores Dependent on Temporal Orientation

SOA	250 ms				1,000 ms			
Factor	Accounted Variance (%)		Latency to Peak Loading (sec)		Accounted Variance (%)		Latency to Peak Loading (sec)	
1	41.566		0.120		26.641		-0.700	
2	11.842		1.060		37.626		0.840	
3	42.757		1.980		29.240		2.120	
	Factor Scores, SOA 250 ms				Factor Scores, SOA 1,000 ms			
Temporal Orientation	Chronological		Reverse		Chronological		Reverse	
Factor	M	SE	M	SE	M	SE	M	SE
1	0.164	0.185	-0.164	0.178	0.186	0.177	-0.186	0.184
2	0.080	0.181	-0.080	0.186	0.024	0.190	-0.024	0.178
3	-0.161	0.183	0.161	0.181	-0.275	0.165	0.275	0.188

Figure Captions

Figure 1. Analysis of chronological vs. reverse items for SOA 250 ms (left panels) vs. SOA 1,000 ms (right panels): mean pupillary responses, relative to a baseline. (A) Target-locked averaging. A constant time window was chosen for averaging: from presentation of the target 2,300 ms onwards. Vertical lines represent the mean reaction times of chronological vs. reverse items. The initial values of the four curves were set to value 0. (B) Probe-locked averaging. Note that probe duration is different for the two SOA conditions (250 vs. 1,000 ms). The zero value on the x-axis, together with the vertical dotted line, represents the time point of target presentation.

Figure 2. Analysis of experimental vs. filler items for SOA 250 ms (left panel) vs. SOA 1,000 ms (right panel): probe-locked averaging of pupillary responses, relative to a baseline. Vertical lines represent the mean reaction times for experimental vs. filler items. The zero value on the x-axis, together with the vertical dotted line, represents the time point of target presentation.

Figure 3. Principal component analysis on pupil data for meaningfully related probe-target pairs. For each SOA condition, three factors were extracted. Displayed are factor loadings > .40 only. In each plot, the vertical solid line represents the mean reaction time (RT) across chronological and reverse items. The factors are numbered and displayed according to the time course of the pupillary response.

Figure 1

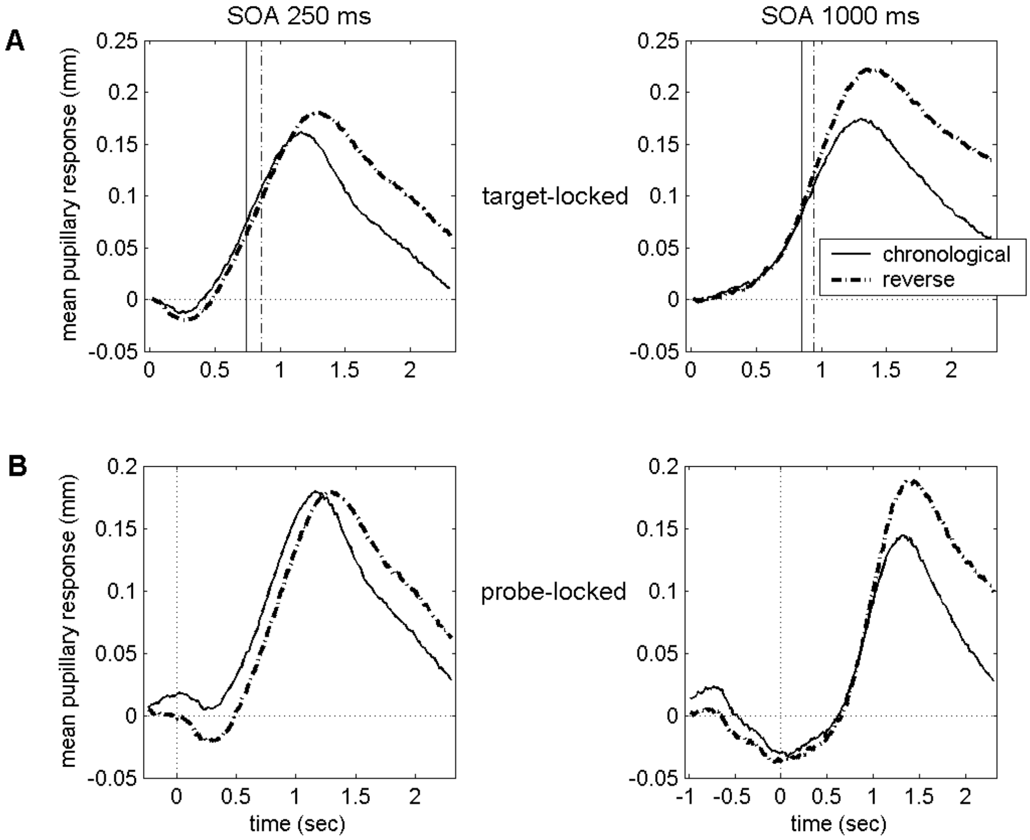

SOA 250 ms
SOA 1000 ms
A
B
mean pupillary response (mm)
target-locked
probe-locked
chronological
reverse
time (sec)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-1
-0.5
0.5
1
1.5
2

Figure 2

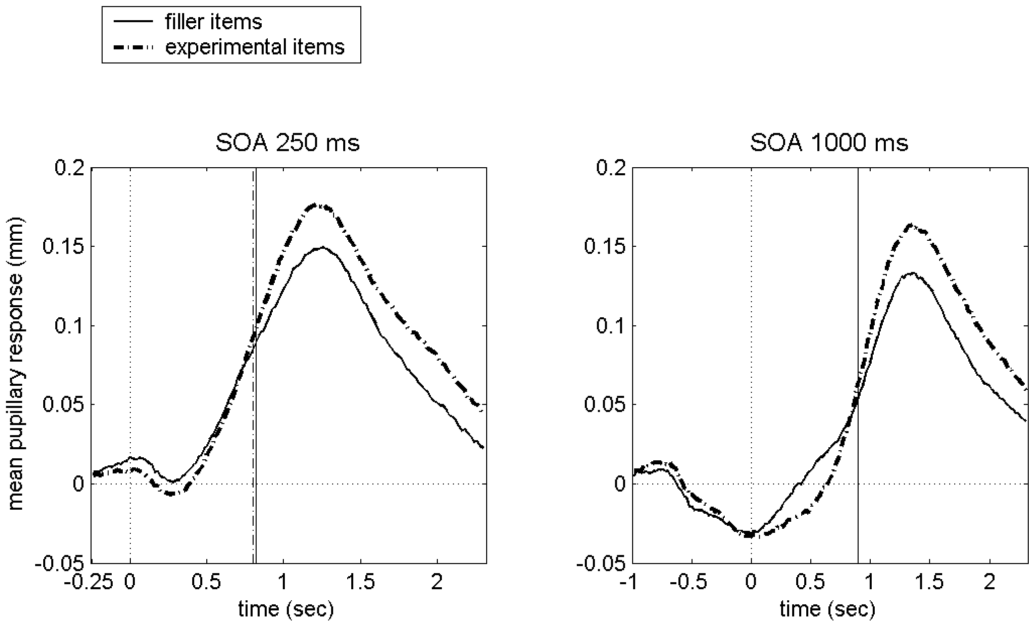
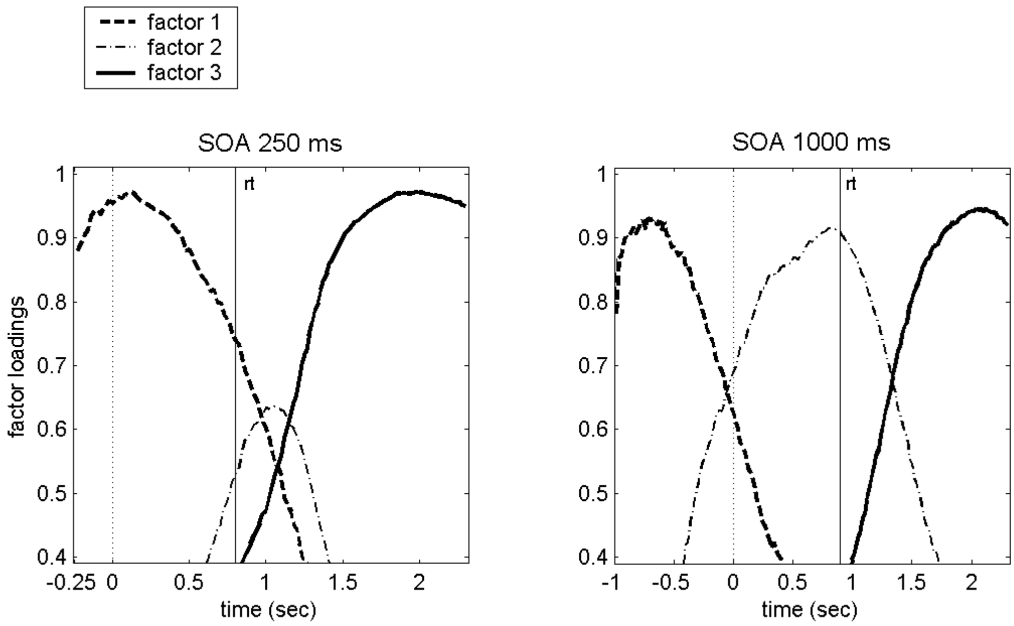

filler items
experimental items
SOA 250 ms
SOA 1000 ms
mean pupillary response (mm)
time (sec)
time (sec)

Figure 3


factor 1
factor 2
factor 3
SOA 250 ms
SOA 1000 ms
factor loadings
rt
rt
time (sec)
time (sec)